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Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute

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ABSTRACT

This study assessed the environmental impacts of natural coarse aggregate and electric arc furnace aggregate production, and the impacts of paving blocks production using both aggregates in the proportion of 50%. The life cycle impact assessment has been performed by using the IMPACT 2002 + method, considering the impact categories of carcinogens, non-carcinogens, respiratory inorganics, terrestrial ecotoxicity, global warming and non-renewable energy. In the electric arc furnace aggregate production, the results indicate that metal recovering is responsible for the negative impacts (84%); electricity, diesel and lubricating oil consumption contribute for respiratory inorganics, global warming, non-renewable energy and non-carcinogens impact categories, while transport contributes for the same categories and terrestrial ecotoxicity. Considering the paving blocks production, cement has the highest contribution for all impact categories, except terrestrial ecotoxicity; the paving blocks produced with electric arc furnace aggregate present the lowest impacts for the climate change and ecosystem quality categories, and avoided impacts for human health and resources damage categories.

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1. Introduction

Electric arc furnace slag (EAFS) is a by-product generated in the semi-integrated steelmaking process, which uses metal scrap as the basic raw material, and for that reason has been considered the most competitive and sustainable process for steel production, representing over 40% of the steel produced worldwide (Pellegrino et al., 2013). After cooling, crushing and sieving, the EAFS is usually named electric arc furnace aggregate (EAFA), and may substitute conventional aggregates in several construction applications.

Chemical and physical properties of EAFS may vary according to specific characteristics of the steelmaking process; generally its visual appearance is similar to the natural aggregates, especially due to the dark gray color. Arribas et al. (2015) point out that EAFS chemical composition is made of 80% in weight of calcium, iron and silicon oxides, and the 20% remaining of aluminum, magnesium, manganese and phosphorus oxides. The content of iron oxides increases the hardness and density of EAFS. According to Manso et al. (2006), the high density is useful when the slag is incorporated in concrete for use in blocks for containment barriers, foundations, shoring walls, sound barriers, among other applications; instead, the higher weight may interfere in the transportation costs (Faleschini et al., 2014); and further, EAFS is usually an inert material, presenting no risks of leaching hazardous substances into the environment.

Considering the need of reducing natural resources consumption, studies have been carried out in order to evaluate the technical aspects related to the use of EAFS as an alternative material, notably as substitute of natural coarse aggregate (NCA) in concretes (Adegoloye et al., 2016; Manosi et al., 2016; Rondi et al., 2016), and in the manufacturing of cement (Iacobescu et al., 2011), ceramic tile (Teo et al., 2014), mortar (Kuo et al., 2014) and geopolymer concrete (Khan et al., 2016).

However, when the environmental aspects are comprehensive analyzed, in some cases the use of alternative materials may create as such impacts that override its benefits, and thereby, the life cycle assessment (LCA) methodology may be used to compare scenarios (Mladenovic et al., 2015), and particularly, to compare different products with the same functionality (Turk et al., 2015), as for example, the use of EAFS and NCA in concrete production.

Ferreira et al. (2016) conducted a LCA study to compare the use of hot bituminous mixtures (with natural aggregates and 75% of EAFS substitution) for road construction. For both scenarios, the bitumen consumption presented the remarkable impacts,

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especially for ozone depletion, due to the crude oil refining process; the use of EAFS showed a reduction of approximately 10% in the environment impacts for most impact categories. The authors emphasize the importance of analyzing the slag characteristics, especially porosity, as it may increase asphalt consumption. Mladenovic et al. (2015) have also evaluated the use of EAFS in asphalt mixes production. The road operation and maintenance was not considered, as the authors assumed that the environmental burdens do not differ for the two asphalt wearing courses, based on the results of laboratory tests. The results have shown that the use of EAFS reduces the impacts related to the acidification, eutrophication, photochemical ozone creation potential and human toxicity categories and, the global warming category is conditioned to the delivery distance of EAFS; a sensitivity analysis found that when this distance exceeds the distance of the conventional aggregate by about 100 km, the use of slag aggregate is effective from the perspective of the acidification, eutrophication and photochemical ozone creation potential categories.

Faleschini et al. (2014) compared the impacts of conventional concrete and concrete produced with 100% of EAFS substitution, and found that 1 t of natural aggregate increases in 35% the emissions of the impact categories evaluated. The concretes presented similar environmental impacts, as the cement is the main contributor for the emissions, and the concrete produced with EAFS require more cement in its composition, due to the higher porosity. Anastasiou et al. (2017) conducted a comparative LCA for three concrete products, and found a small reduction in CO_2 emissions derived from the use of EAFS. The authors pointed out that more significant reductions in CO_2 emissions could be achieved by reducing the cement content in concrete.

The motivation of this study comes from the need to further understand the environmental impacts of the use of EAFS as an alternative aggregate in paving blocks production; firstly, because Brazil is among the world's largest steel producers (and consequently, produces large amounts of steel slags), and secondly, due the fact that the paving blocks have been extensively used, as a result of their technical, economic, social and environmental benefits.

The main objective of this study is therefore, to compare the life cycle impacts of concrete paving blocks manufactured with partial substitution of natural coarse aggregate by electric arc furnace slag aggregate, for use in light vehicle traffic, in the Brazilian context. The study provides a detailed LCI on the production of aggregates from EAFS and paving blocks, and a reliable and scientific assessment of potential environmental impacts of these materials.

2. Methodology

This study was conducted in two major steps: (1) paving blocks designing, laboratorial scale production and characterization; (2) comparative life cycle assessment of paving blocks produced with natural coarse aggregate (NCA) and electric arc furnace aggregate[1] (EAFA). Fig. 1 summarizes the methodology used in the study.

2.1. Paving blocks production and characterization

A CPV ARI Portland cement (equivalent to ASTM type III and high early strength) was used. The EAFA, crushed by the producer and supplied with particle sizes between 4.75 and 9.51 mm, was previously tested for expansibility potential,[2] according to the Brazilian Standard ABNT NBR 16364:2015 resulting in a value of 0.05%. Leaching tests have been performed according to the Standard ABNT NBR 10004:2004, attesting that potential toxic compounds are under the limit values of the Brazilian Standards, and that the slag is classified as non-hazardous waste. These results indicate that the EAFA may be safely used as natural aggregate substitute without risks of expansion or hazardous substances leaching.

Table 1 lists the physical properties of the aggregates and cement. The specific mass was determined according to the Standards ABNT NBR NM 23:2001 (cement), ABNT NBR NM 52:2009 (sand and stone dust), and ABNT NBR NM 53:2009 (NCA and EAFA); the water absorption according to ABNT NBR NM 30:2001 (sand and stone dust) and ABNT NBR NM 53:2009 (NCA and EAFA); and the particle size distribution of fine and coarse aggregates according to ABNT NBR 248:2003.

A reference concrete with the ratio 1/1.95/30.04/0.33/0.55 (cement/sand/natural coarse aggregate/stone dust/water-cement) was prepared, and then the NCA was replaced by EAFA in the proportions of 25%, 50%, 75% and 100%, considering the materials density. The water/cement ratio (0.55) and the cement content (370 kg/m^3) were maintained constant for all mixtures.

The consistency of the fresh concrete was determined by the slump test, according to the Standard ABNT NBR NM 67:1998. In total, 16 paving blocks of each EAFA percentage were produced by using rectangular plastic molds (200 × 100 × 60) mm^3; the blocks were cured in humid chamber and then demolded (Fig. 2); 12 blocks were used for compressive strength test (at 7 and 28 days) and 4 blocks for water absorption test according to ABNT NBR 9781:2013.

Table 2 shows the results of the concrete consistency (slump test), compressive strength and water absorption tests. The Brazilian Standard ABNT NBR 9781:2013 requires values of compressive strength ≥35 MPa, and water absorption ≤6%, at 28 days of cure, for use in light vehicle traffic; the paving blocks with 75% and 100% of EAFA did not met the requirement for water absorption, however the values are very close to the threshold limits. Thus, these results ensure that blocks with 25% and 50% of EAFA may be used in light vehicle traffic, in real conditions.

2.2. Environmental analysis of concrete paving blocks

The attributional LCA study was carried out according to the requirements of ISO 14040 and 14044 standards (ISO, 2006a, 2006b), by means of its four major stages: goal and scope definition; life cycle inventory (LCI); life cycle impact assessment (LCIA) and interpretation.

2.2.1. Goal and scope definition

The goal of the study is to compare the environmental impacts of conventional paving blocks and paving blocks with 50% EAFA addition, as this ratio met the requirements for compressive strength and water absorption. The functional unit was defined as 1t for the production of NCA and EAFA, and 1 m^2 of paving blocks (corresponding to 50 paving blocks of 100 mm × 200 mm × 60 mm each).

The system boundaries for paving blocks production with NCA and EAFA are shown in Fig. 3. The stages of use, maintenance and final disposal of paving blocks were excluded, as they have similar performance and significant differences during the lifespan are not expected.

The base case scenario considered the real distance from NCA

[1] In this study, the electric arc furnace slag (EAFS) after crushing and sieving is named as electric arc furnace aggregate (EAFA).

[2] The volumetric expansion of EAFS is a major concern, due to the potential presence of free calcium and magnesium oxides, which may cause hydration and expansion once the slag is in contact with water in the concrete mixture. The use of EAFS as coarse aggregate is currently accepted, whereas the maximum volumetric expansion be 1% (Arribas et al., 2015).

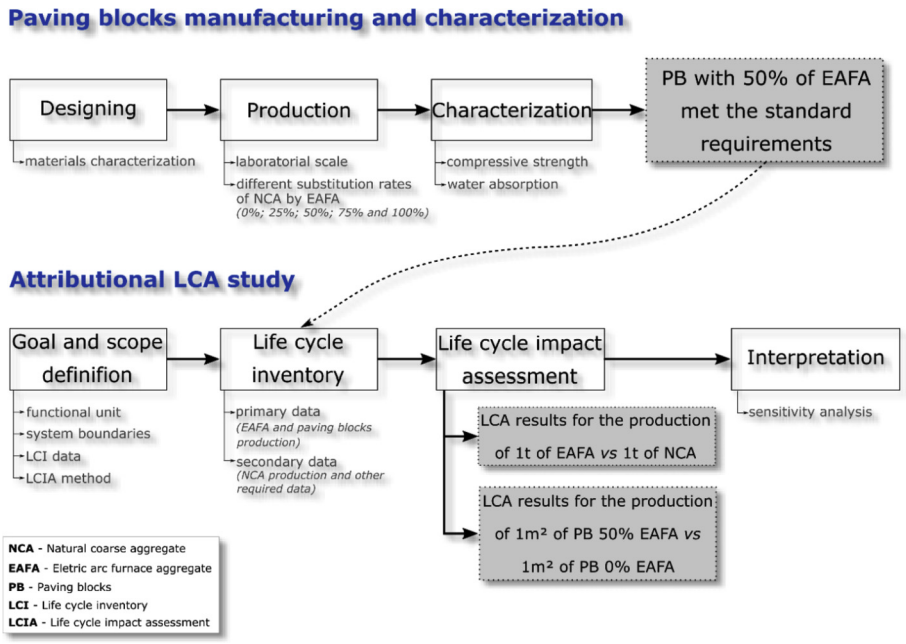
Paving blocks manufacturing and characterization
Designing
Production
Characterization
PB with 50% of EAFA met the standard requirements
materials characterization
laboratorial scale
different substitution rates of NCA by EAFA (0%; 25%; 50%; 75% and 100%)
compressive strength
water absorption
Attributional LCA study
Goal and scope definifion
Life cycle inventory
Life cycle impact assessment
Interpretation
functional unit
system boundaries
LCI data
LCIA method
primary data (EAFA and paving blocks production)
secondary data (NCA production and other required data)
sensitivity analysis
LCA results for the production of 1t of EAFA vs 1t of NCA
LCA results for the production of 1m² of PB 50% EAFA vs 1m² of PB 0% EAFA
NCA - Natural coarse aggregate
EAFA - Eletric arc furnace aggregate
PB - Paving blocks
LCI - Life cycle inventory
LCIA - Life cycle impact assessment

Fig. 1. Schematic representation of the methodology adopted in this study.

Table 1
Physical characteristics of the materials used in paving blocks manufacturing.

	Specific mass (kg/m^3)	Water absorption (%)	Maximum diameter (mm)	Fineness modulus
Cement	3130	–	–	–
Sand	2610	0.20	1.2	1.67
Stone dust	3650	3.4	4.8	2.25
NCA	3060	4.8	9.5	5.75
EAFA	3640	2.25	9.5	5.80

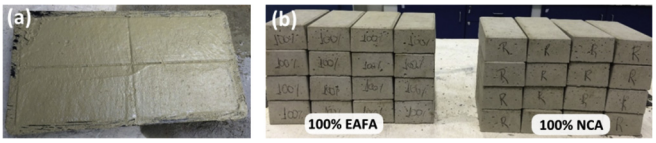

Fig. 2. Paving blocks in rectangular plastic molds (a); paving blocks after cure (b).

and EAFA production sites to the paving blocks facility (9.7 km and 26.6 km, respectively); in the sensitive analysis, alternative transport scenarios were evaluated. Capital goods, such as infrastructure of the facilities, buildings, equipment and lorries, and their maintenance, were intentionally excluded, since no reliable data were available.

LCA modelling has been performed using the SimaPro® 8.0.2 software, while generic data for supporting processes derive from the Ecoinvent v.3.01 (2014) and US LCI (2003) databases, and updated with Brazilian data where possible.

2.2.2. Life cycle inventory

The LCI drafting comprises the quantification of inputs (energy and mass flows) and outputs (emissions to air, water, soil and solid wastes) of the unit processes included at the system boundaries according to the functional unit (Arena et al., 2003; Marinković et al., 2010; Vieira et al., 2016).

The direct burdens for the LCI of EAFA and paving block production were obtained from technical visits in facilities located in Southeast Brazil in 2016, and they are related to the materials and energy consumption. Technical reports on the equipment configurations and, in particular, mass flow analysis for the EAFA production, were provided by the facilities, which allowed a reliable information for the validation of LCI input data. The direct burdens for the LCI of NCA production used the data of a previous study developed by Rosado et al. (2017), which is based in primary data collected in a basalt quarry located in the same area of this study; therefore no data adaptation to geographic, temporal and technological coverage was necessary. The remaining burdens, mainly

Table 2
Results for concrete consistency, compressive strength and water absorption.

	Slump (mm)	Compressive strength (MPa)		Water absorption (%)
		7 days	28 days	28 days
Reference concrete	20	37.1	49.1	4.8
25% EAFA	55	40.6	47.0	5.5
50% EAFA	60	37.7	45.4	5.9
75% EAFA	77	34.6	43.4	6.1
100% EAFA	90	32.9	40.8	6.2

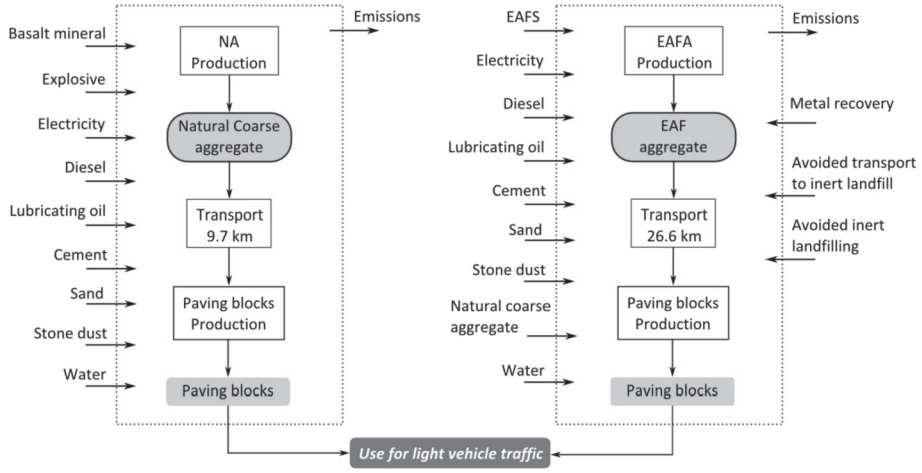

Fig. 3. System boundaries for NCA, EAFA and paving blocks production. Transport distances refer to the current situation (base case scenario).

indirect and avoided, were obtained from databases.

The processes for each scenario are presented in Fig. 4. The environmental burdens refer to the electricity consumption considering the Brazilian energy mix (Table 3), and the consumption of diesel and other materials in the different stages of the production of NCA, EAFA and paving blocks.

Details of material and energy inputs of the life cycle of NCA, EAFA and paving blocks are presented in Appendix A of this study. The burdens related to the steelmaking manufacturing and EAFS cooling were not considered, as these processes occur regardless of slag is used as aggregate or landfilled.

After its production in the electric arc furnace, the EAFS is led to an open air area in the steelmaking facility for cooling, and then is transferred to a dump truck (by using a wheel loader), and

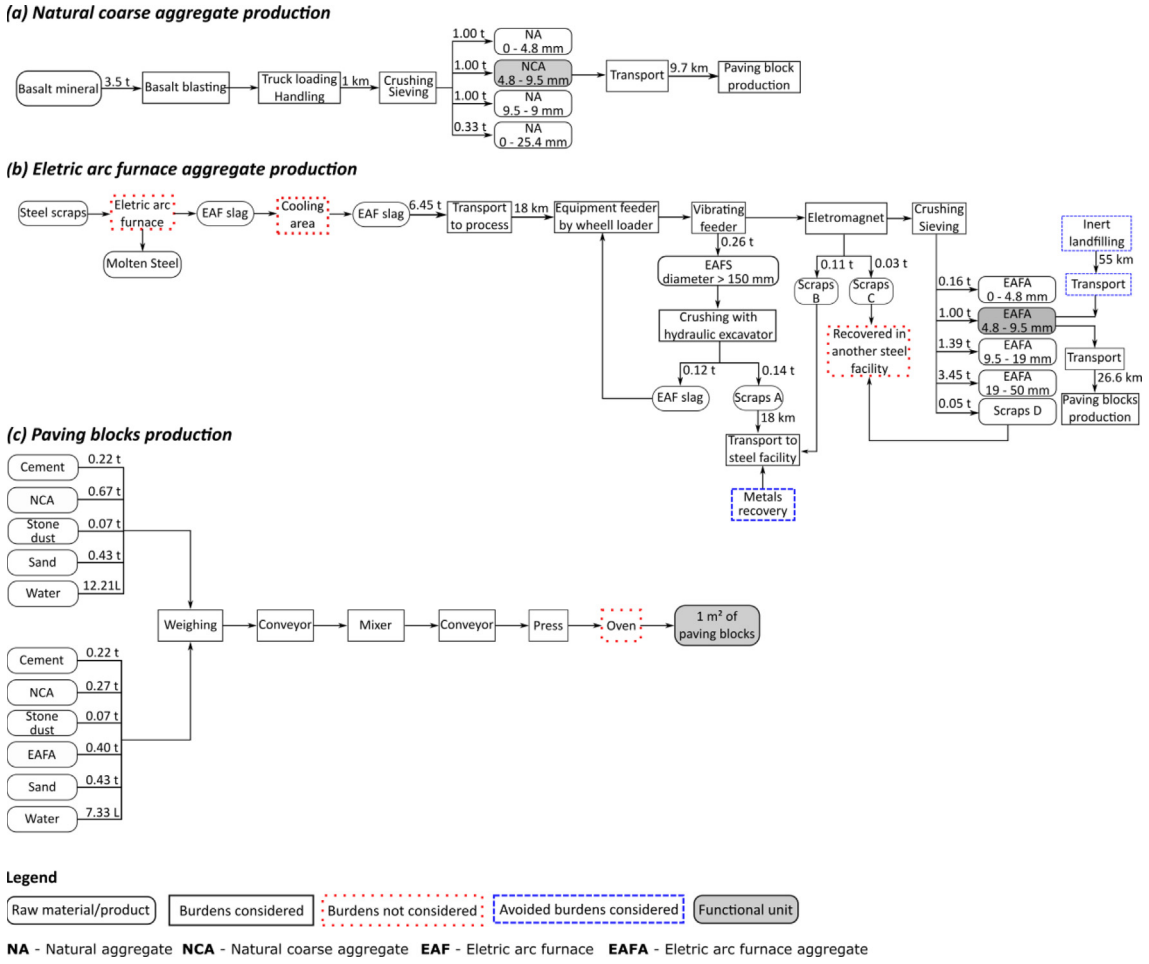

Fig. 4. Schematic representation of (a) NCA production, (b) EAFA production and (c) paving blocks production, with the considered and neglected environmental burdens.

Table 3
Brazilian electric mix (Ecoinvent, 2014).

Electricity/Heat	%
Electricity production, hydro, reservoir, tropical region	78.63
Electricity production, natural gas	5.99
Heat and power co-generation, wood chips	4.09
Electricity production, oil	3.62
Electricity production, nuclear	2.82
Sugar cane production with ethanol by-product	1.82
Electricity production, lignite	1.35
Treatment of blast furnace gas	0.82
Treatment of coal gas	0.35
Ethanol production from sugar cane	0.29
Electricity production, wind	0.14
Electricity production, hard coal	0.06

transported for 18 km to the recycling facility (where is also located the company's scrap yard); thus, as the truck returns to the steelmaking facility loaded with metal scrap (for use in another product system), the transport impacts were calculated considering one way trip.

The recycling facility occupies a total area of 788,972 m^2, with a production capacity of 385 t/day (operating 9 h/day and 6 days/week). In the recycling process a vibrating feeder separates the slag with diameter higher than 150 mm, which represents around 4% of the total EAFS. This high diameter material is crushed by a hydraulic excavator, allowing the recovery of 55% in weight of metal scrap (Scrap A) that returns to the electric arc furnace as raw material; the 45% of EAFS is sent back to the recycling process, and passes through a magnetic separator that removes around 2.1% of metals (1.7% of Scrap B that returns to the steelmaking facility, and 0.4% of Scrap C that is sent to an external recycling facility); the remaining EAFS is then crushed and separated in a vibratory sieve, producing the electric arc furnace aggregate (EAFA) in the following diameter sizes: 0–4.75 mm (2.5%), 4.75–9.51 mm (15.5%), 9.51 mm-19 mm (21.5%) and 19 mm-50.8 mm (53.5%). In addition, 0.8% of remaining scrap (Scrap D) is removed in the vibratory sieve and sent to an external recycling facility along with Scrap C, since they cannot be reintegrated into the steelmaking process, due to the quality requirements. Therefore, this study only considered the environmental benefits of metal recovery from scraps A and B.

The paving blocks facility occupies an area of 63,619 m^2, with a production capacity of 81,500 blocks of $100 \times 200 \times 60$ mm^3/day, operating 9 h/day and 5 days/week. The raw materials (water, cement, sand, stone dust and coarse aggregate) are stored in stalls and silos which are connected to treadmills which weigh and transport the materials to the mixer. After the concrete mixture, the blocks are molded, placed into a storage shelf and sent to a cure oven for 48 h. The environmental burdens of the curing stage were not considered, due to the lack of data on energy consumption.

2.2.3. Life cycle impact assessment method

The LCIA has been performed by using the IMPACT 2002 + method, according to the mandatory elements (selection of impact categories, classification and characterization) and normalization in person year (average impact in a specific category caused by a person during one year). The IMPACT 2002 + is classified as a midpoint and endpoint method, because it combines 15 impact (midpoint) categories: human toxicity (carcinogens and non-carcinogens), respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, nonrenewable energy, mineral extraction; and four damage (endpoint) categories: human health, ecosystem quality, climate change and resources (Jolliet et al., 2003). Fig. 5 presents the relevant impact categories for this study, which have been selected based on the analysis of the normalized impacts for all midpoint categories (Fig. 1b – Appendix B), and represent 99% of the total impacts.

3. Results and discussion

This section presents the results of the life cycle assessment study, and the results of two sensitivity analysis performed to evaluate the impacts of increasing the content of EAFA in the paving blocks, and the influence of transport distances.

3.1. Life cycle impact assessment

The normalized results for the production of 1 t of EAFA with particle size 4.8–9.5 mm (Fig. 6) show significant avoided impacts (84%) from metal recovering (scraps A and B), especially for respiratory inorganics, global warming and non-renewable energy. The avoided impacts from EAFS transport to the landfill and landfilling are related to the same impact categories, but to a lesser extent (6%), because EAFS is classified as non-hazardous waste, and thus, the impacts of its landfilling are not significant.

The impacts from electricity, diesel and lubricating oil consumption for EAFA production present the major contributions for respiratory inorganics, global warming, non-renewable energy and non-carcinogens categories. The EAFS transport for EAFA production contributes for respiratory inorganics, terrestrial ecotoxicity, global warming and non-renewable energy categories, while the EAFA transport for paving blocks production does not have significant contribution, representing 1% of the total impacts.

Table 4 shows the normalized results of impact assessment for each stage of EAFA production. The electricity consumption in the crushing process is the main contributor for carcinogens and non-carcinogens categories. The diesel consumption in the hydraulic excavator, used to comminute the slags with diameter higher than 150 mm, is the main contributor for respiratory inorganics. The transport of EAFS from the steelmaking facility to the recycling facility presents the highest impacts for terrestrial ecotoxicity, global warming and non-renewable energy categories. The metal recovering from EAFS results in environmental benefits in every impact categories, as it reduces the demand for pig iron. Consequently, there is a reduction in the emissions related to energy and materials used for iron ore extraction and pig iron production.

A contribution analysis was conducted in order to highlight the main emissions responsible for the potential environmental impacts of EAFA production (Figs. 2b–7b - Appendix B).

The electricity consumption, mainly in the EAFS crushing stage, contributes for the impacts of carcinogens and non-carcinogens; the first category is influenced by aromatic hydrocarbons emissions to the air, from the natural gas production in the Brazilian energy mix (Fig. 2b – Appendix B), while the second, by arsenic emissions to the soil related to the energy from sugar cane bagasse (Fig. 3b – Appendix B), due to the use of the herbicide monosodium methyl arsenate in the crops (Serodio, 2014).

The diesel consumption in wheel loader and hydraulic excavator produces air emissions of polycyclic aromatic hydrocarbons (PAHs) (Fig. 2b – Appendix B), nitrogen oxides (Fig. 4b – Appendix B) and carbon dioxide (Fig. 6b – Appendix B), which influence the carcinogens, respiratory inorganics and global warming categories, respectively. In turn, the production of diesel results in barium emissions into the water (Fig. 3b – Appendix B), influencing the non-carcinogens category.

Though EAFS is transported for a shorter distance to produce the EAFA (18 km), compared to the distance of EAFA to produce the

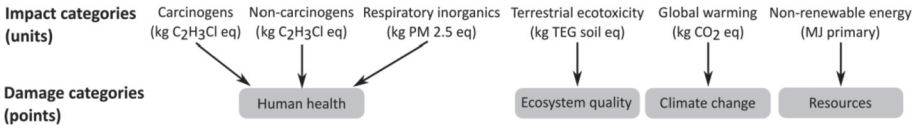

Fig. 5. Impact (midpoint) and damage (endpoint) categories considered in the study.

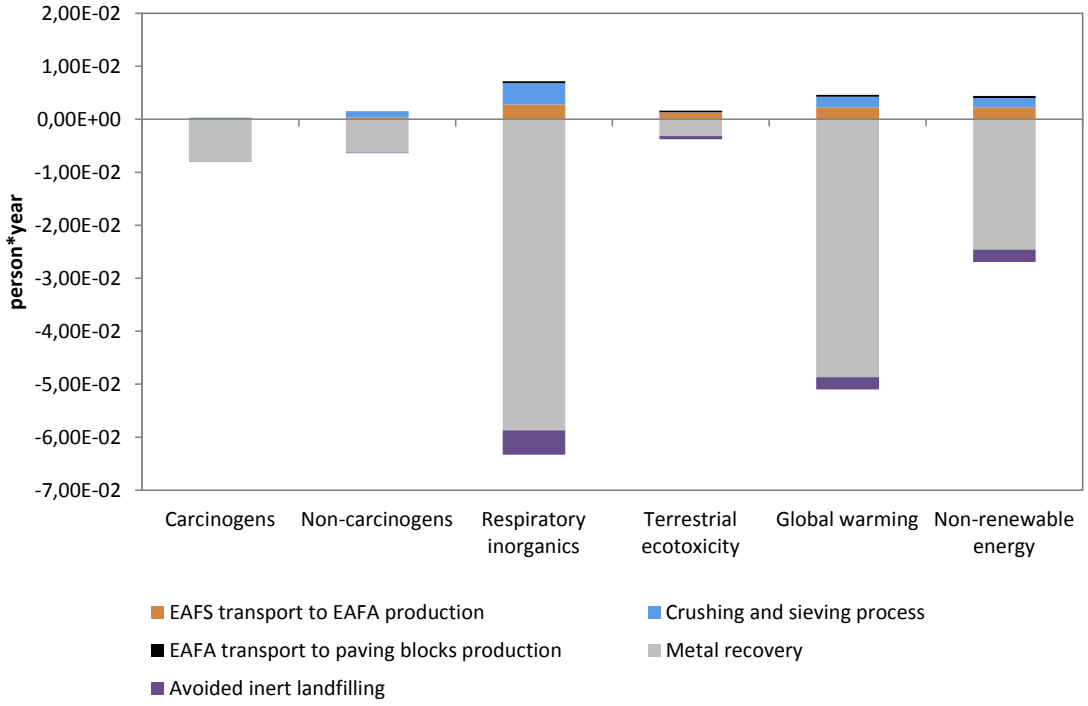

Fig. 6. Normalized results of impact assessment for electric arc furnace aggregate in the base case scenario.

Table 4
Normalized results of impact assessment for the EAFA production stages.

EAFA production	Carcinogens	Non-carcinogens	Respiratory inorganics	Terrestrial ecotoxicity	Global warming	Non-renewable energy
Wheel loader for truck loading	8,58E-06	1,72E-04	1,44E-03	1,86E-07	6,27E-04	6,05E-04
EAFS transport to EAFA production	1,25E-05	1,85E-04	1,37E-03	**1,29E-03**	**1,62E-03**	**1,64E-03**
Wheel loader for handling	8,58E-06	1,72E-04	1,44E-03	1,86E-07	6,27E-04	6,05E-04
Vibrating feeder	1,08E-06	4,55E-06	3,37E-06	3,49E-07	3,09E-06	1,95E-06
Hydraulic excavator to size reduction	1,25E-05	2,50E-04	**2,10E-03**	2,70E-07	9,12E-04	8,81E-04
Crushing	**1,30E-04**	**5,46E-04**	4,04E-04	4,18E-05	3,71E-04	2,35E-04
Conveyor	1,56E-05	6,56E-05	4,85E-05	5,02E-06	4,45E-05	2,81E-05
Vibrating sieving	7,79E-06	3,28E-05	2,43E-05	2,51E-06	2,23E-05	1,41E-05
Conveyors	1,56E-05	6,56E-05	4,85E-05	5,02E-06	4,45E-05	2,81E-05
Oil lubricating	1,73E-07	7,93E-08	2,51E-06	5,30E-08	1,92E-06	1,05E-05
EAFA transport to paving block production	2,85E-06	4,24E-05	3,14E-04	2,95E-04	3,72E-04	3,75E-04
Metal scraps transport	4,83E-07	7,17E-06	5,32E-05	4,99E-05	6,29E-05	6,34E-05
Metal recovery	**−8,00E-03**	**−6,31E-03**	**−5,88E-02**	**−3,19E-03**	**−4,87E-02**	**−2,47E-02**
Avoided transport to inert landfill	−5,90E-06	−8,76E-05	−6,50E-04	−6,10E-04	−7,68E-04	−7,75E-04
Avoided inert landfilling	−5,30E-06	−2,54E-06	−6,60E-04	−4,48E-06	−2,57E-04	−2,53E-04

paving blocks (26.6 km), EAFS has a higher density and therefore, is the main contributor to the respiratory inorganics, due to nitrogen oxides, particulate matter (<2.5 μm) and sulfur dioxide emissions (Fig. 4b - Appendix B). The wear of tires and brakes contribute to terrestrial ecotoxicity, due to the emissions of zinc to the soil and air, and copper to the air (Fig. 5b – Appendix B). Moreover, the EAFS transport to produce the EAFA causes the emission of 16 kg CO_2 eq/t of EAFA, and the transport of EAFA to produce the paving blocks and the transport of the recovered metal cause the emission of 5 kg CO_2 eq/t of EAFA, which influence the global warming category.

EAFS recycling avoids the emissions of benzo(a) pyrene, PAHs and particulate matter (<2.5 μm) from coke (used as fuel in the pig iron production), resulting in negative impacts in the carcinogens (Fig. 2b – Appendix B) and respiratory inorganics categories (Fig. 4b – Appendix B). The recovered metal replaces the pig iron in steel production, avoiding the emissions of nitrogen oxides and aluminum from the extraction of iron ore; the first contributes for the inorganics and the second, for the terrestrial ecotoxicity category (Fig. 5b – Appendix B), both from the iron ore blasting. In addition, the metal recovering avoids the production of sinter

(agglomerate of iron ore fine particles) and consequently, the emissions of dioxins (TCDD) and sulfur dioxide, resulting in avoided impacts for carcinogens, non-carcinogens and respiratory inorganics. The reduction in pig iron production, avoids the emission of 454 kg of CO_2, influencing the global warming category.

The EAFS diversion from landfill avoids emissions of PAHs, nitrogen oxides, particulate matter (<2.5 μm) and carbon dioxide, related to the use of diesel in the landfill operation, and the emissions of nitrogen oxides, particulate matter (<2.5 μm), zinc, copper and carbon dioxide from the slag transport to the landfill.

In general, the non-renewable energy category (Fig. 7b - Appendix B) is influenced by the diesel consumed in transport stages, avoided coal consumption due to metal recovery, and avoided diesel consumption from EAFS transport and landfilling.

The comparison of normalized results of potential impacts of aggregates production shows negative impacts for all categories in EAFA production (Fig. 7), as it recovers approximately 4% of metal. Turk et al. (2015) conducted a LCA study on EAFS use in concrete, and also found that the main benefits of slag recycling are related to metal recovering (considered as avoided pig iron production).

According to Rosado et al. (2017), the production of natural aggregate contributes mainly to terrestrial ecotoxicity and respiratory inorganics categories, due to the basalt extraction. As previously mentioned, the use of electricity in basalt crushing contributes to the non-carcinogens category. The other impact categories are influenced by the basalt transport to the process and the aggregate transport to the paving blocks facility.

The contribution analysis of the potential impacts related to the materials and electricity used for paving block production (Fig. 8) shows that cement has the highest contribution for all impact categories (except terrestrial ecotoxicity), due to the CO_2 emission during the clinker calcination, and the use of fossil fuels (Marinković et al., 2010). Terrestrial ecotoxicity is influenced by natural aggregates (coarse aggregate and stone dust) due to basalt extraction; electricity consumption is relevant for carcinogens and non-carcinogens, and the impacts of sand and stone dust are not significant.

The paving blocks produced with 50% of EAFA presents lower impacts, mainly due to the metal recovering. In fact, the EAFS recycling process considered in this study, was initially implemented to recover the metal scrap, and later, in order to save final disposal costs, the use of the slag as aggregate was adopted as a waste management option. However, it is important to note that due to the use of natural aggregates and cement in paving blocks manufacturing, the positive impacts overcome the avoided impacts for the terrestrial ecotoxicity and global warming categories.

In summary, for the impact categories evaluated in this study, and considering a paving block with 50% EAFA addition, the results show that cement contributes for 42% of total impacts, NCA for 3%, sand, dust stone and electricity for 1% each, while the use of EAFA reduces the total impacts by 52%.

Considering the normalized results of the damage categories (Fig. 9), paving blocks produced with 50% EAFA present lower impacts for the climate change and ecosystem quality categories, and avoided impacts for human health and resources categories. The use of damage categories facilitates the understanding of LCA results (Jolliet et al., 2003) and subsidize the decision-making process in industry, government and non-governmental organizations (Nabavi-Pelesaraei et al., 2017). Therefore, these results may provide valuable support for decision makers both in construction and steelmaking sectors, since, as stated by De Feo et al. (2016), it is difficult to take decisions solely on the midpoint impact categories, which may present conflicting results.

3.2. Interpretation

In the sensitive analysis, the environmental impact assessment of paving blocks manufactured with 75% and 100% of EAFA incorporation was evaluated, since the compressive strength met the standard requirements and the water absorption exceeded the

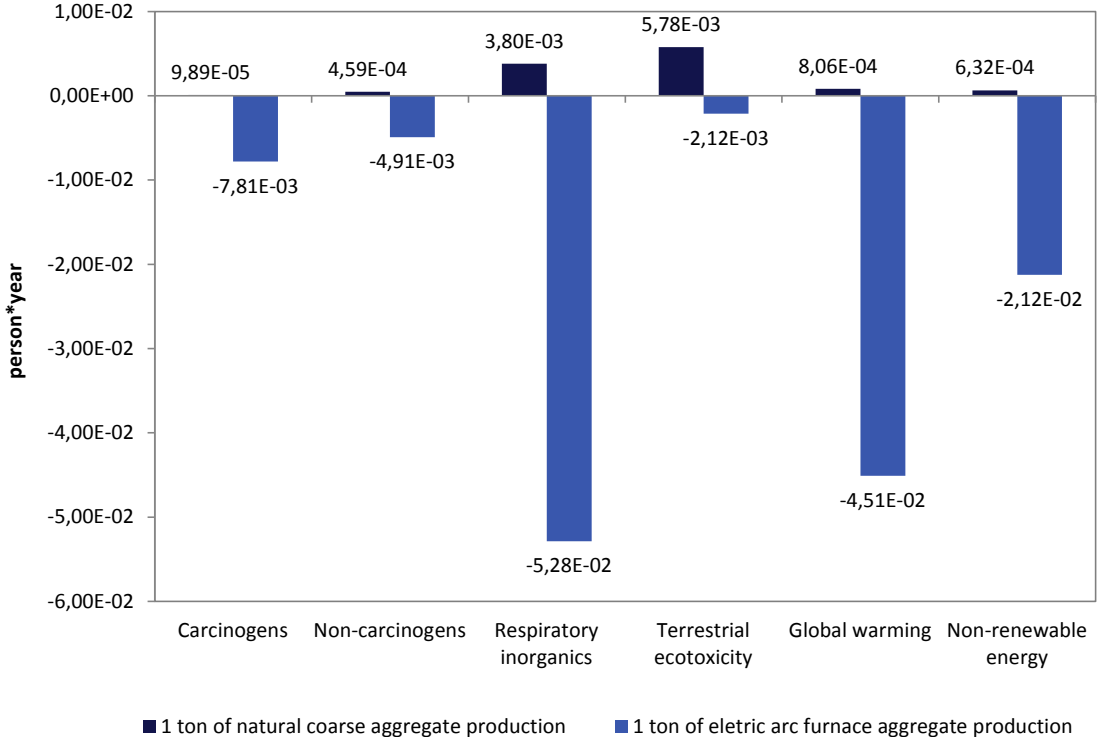

Fig. 7. Comparison of normalized results of impact assessment related NCA and EAFA production.

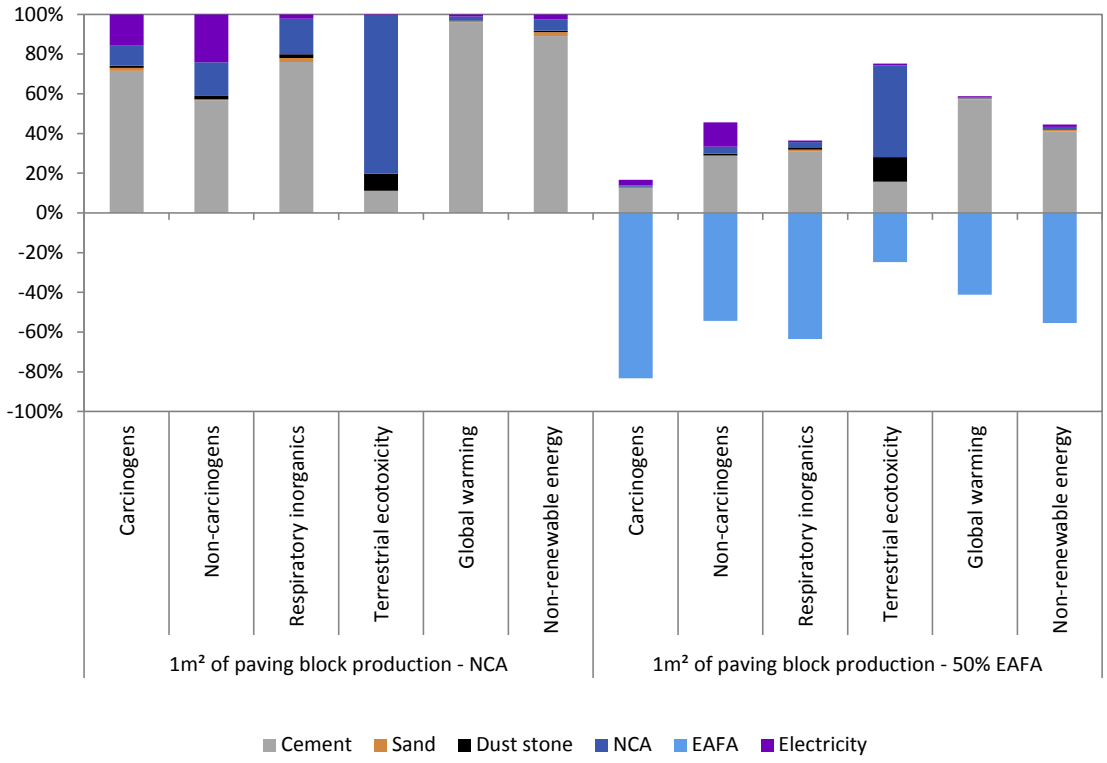

Fig. 8. Contribution of materials and electricity used in the paving blocks production. The percentage refers to the total normalized impacts, for each impact category.

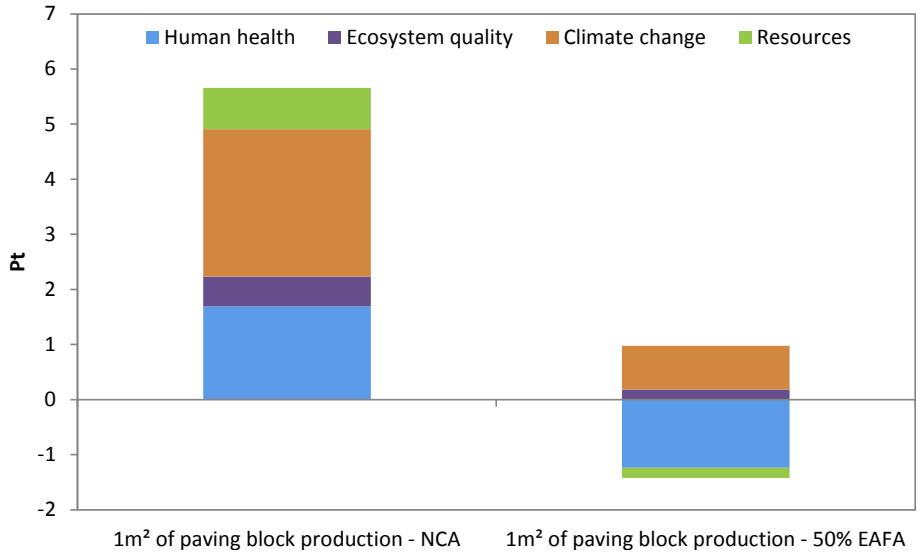

Fig. 9. Normalized results of assessment in terms of damage categories for the paving blocks with NCA and paving blocks with 50% EAFA.

recommended limit in 0.1 and 0.2%, respectively.

As expected, the highest EAFA percentage results in lower environmental impacts for the selected categories (Fig. 10); when the NCA is completely replaced, the paving blocks present avoided impacts for all categories.

In order to determine the scenario in which EAFA results in higher impacts compared to NCA, a simulation of transport distances from the EAFA production site to the paving blocks facility was conducted (Fig. 11), by fixing the distance from the NCA production site in 9.7 km (base case scenario). For terrestrial ecotoxicity the limiting distance from the EAFA production site to the paving blocks facility in order to keep the impacts of EAFA lower is 740 km. It is important to mention that the analysis was performed for all impact categories, however, terrestrial ecotoxicity one stood out over the others.

4. Conclusions

This study assessed the environmental impacts of natural coarse aggregate (NCA) and electric arc furnace aggregate (EAFA) production, and the impacts of paving blocks production using NCA and EAFA in the proportion of 50%, by utilising primary data from

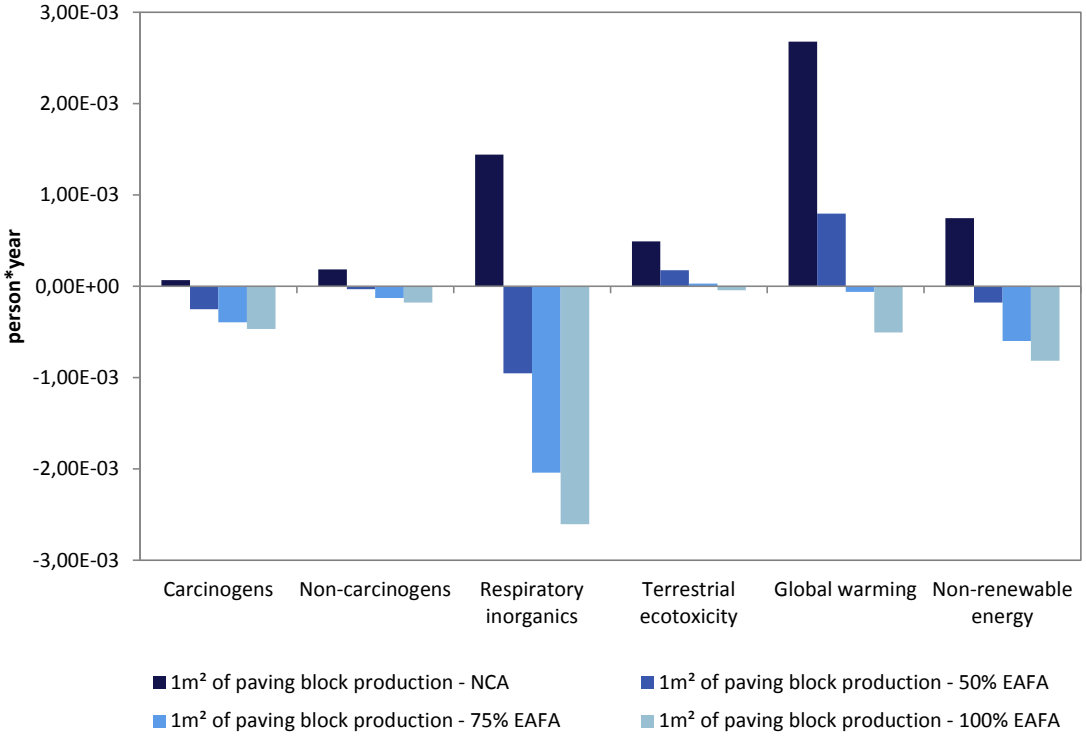

Fig. 10. Normalized results of the sensitivity analysis for paving blocks with NCA and paving blocks with 50%, 75% and 100% EAFA.

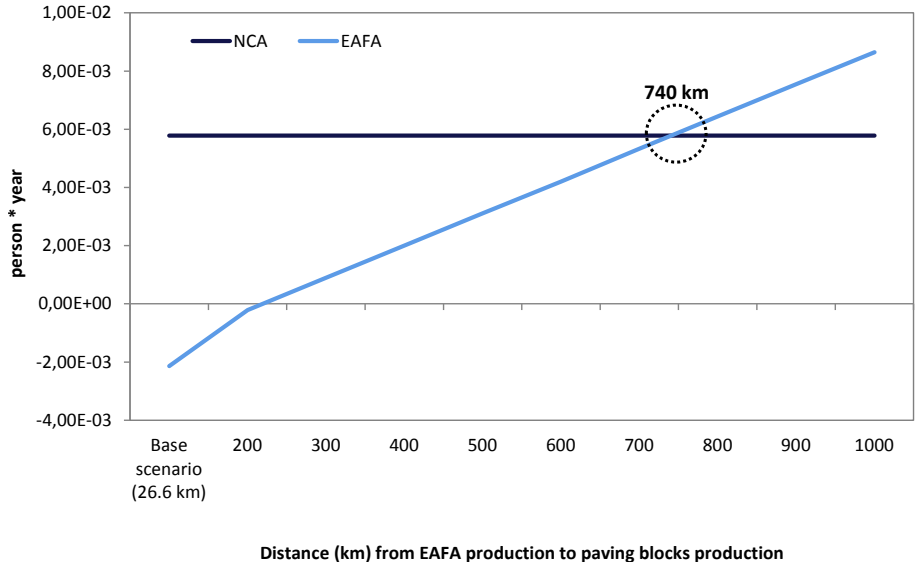

Fig. 11. Sensitivity analysis for the aggregates transport to the paving blocks production, in terms of terrestrial ecotoxicity.

the production systems under analysis, and a standardised attributional LCA procedure.

The obtained results clearly shows the environmental advantages of using the electric arc furnace aggregate in substitution of natural coarse aggregate. Even when the transport distances are significant, the use of the alternative aggregate is advantageous. However, an economic analysis must be conducted, as the higher density of the EAFS may influence the transport costs.

Finally, the results may be useful to similar LCA studies, provided that all the geographical, temporal and technological conditions be considered.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at

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